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Sanal Flow Choking: A Paradigm Shift in Computational Fluid Dynamics Code Verification and Diagnosing Detonation and Hemorrhage in Real-World Fluid-Flow Systems

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The discovery of Sanal flow choking is a scientific breakthrough and a paradigm shift in the diagnostics of the detonation/hemorrhage in real-world fluid flow systems. The closed-form analytical models capable of predicting the boundary-layer blockage factor for both 2D and 3D cases at the Sanal flow choking for adiabatic and diabatic fluid flow conditions are critically reviewed here. The beauty and novelty of these models stem from the veracity that at the Sanal flow choking condition for diabatic flows all the conservation laws of nature are satisfied at a unique location, which allows for computational fluid dynamics (CFD) code verification. At the Sanal flow choking condition both the thermal choking and the wall-friction-induced flow choking occur at a single sonic fluid throat location. The blockage factor predicted at the Sanal flow choking condition can be taken as an infallible data for various in silico model verification, validation, and calibration. The 3D blockage factor at the Sanal flow choking is found to be 45.12% lower than the 2D case of a wall-bounded diabatic fluid flow system with air as the working fluid. The physical insight of Sanal flow choking presented in this review article sheds light on finding solutions, through in silico experiments in base flow and nanoflows, for numerous unresolved problems carried forward over the centuries in physical, chemical, and biological sciences for humankind.

1. Introduction

The narration of physics of real-world fluids may be considered ancient and the basic mathematical models describing physics and the chemistry of fluids are well known for solving varieties of industrial problems of topical interest.[1–4] Admittedly, until the theoretical discovery of the Sanal flow choking phenomenon,[1,5,6] there were no scientific communities/agencies/individual having any mathematical model capable to predict the 3D boundary-layer-displacement-thickness (defined herein as a blockage factor) with molecular precision for the internal flow systems design (both base fluid and nanofluids) and also for the verification of the 3D in silico results for an accurate judgement on the real-world fluid flow characteristics of wall-bounded problems for various industrial applications in physical, chemical and biological sciences. The phenomenon of Sanal

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flow choking is a compressible fluid flow effect caused by the blockage factor, developed in any wall-bounded real-world fluid flow system, irrespective of the incoming flow velocity. The Sanal flow choking occurs at a critical pressure ratio (CPR) in any straight duct with the uniform cross-sectional area at the creeping inflow condition or at a low subsonic inflow condition when the total-to-static pressure ratio reaches the CPR, which is uniquely controlled by the heat capacity ratio (HCR) of the fluid. The Sanal flow choking can also occur in the streamtubes of both the internal and the external real-world fluid flows once the flow between the streamlines reaches the CPR. At this physical condition, if the streamtube shape in any reacting flow is similar to the convergent-divergent (CD) flow passage there are possibilities of the existence of the detonation anywhere in the divergent region of the off-designed CD nozzle-shaped streamtube. Note that at the Sanal flow choking condition the CPR is governed exclusively by the HCR of the incoming fluid.[1,5] In the case of multispecies/composite fluid flows, the Sanal flow choking condition is detected by the lowest values of the HCR of the dominant base fluid or the nanofluid.

The theoretical discovery of the phenomenon of the Sanal flow choking in the real-world fluid flow is a paradigm shift in the diagnostic sciences of the compressible fluid flows for a reliable verdict on various unanswered research topics of contemporary interest.[1,5–10] The mathematical models capable to forecast the exact values of the blockage factor for both 2D and 3D fluid flow cases at the Sanal flow choking condition for adiabatic[1] and diabatic[5,6] fluid flow cases are critically reviewed herein. The beauty and novelty of these models stem from the veracity that at the Sanal flow choking condition for diabatic flows (flows that involve transfer of heat), all conservation laws of nature are satisfied at a unique sonic-fluid-throat location.[1,5] The fact is that at the condition prescribed by the Sanal flow choking model for real-world fluid flows, the internal flow choking due to heating (thermal choking,[3]—Rayleigh flow effect) and that of the frictional effects (Fanno flow effect[3]) converge at a unique location of the fluid-throat, where the Mach number reaches unity. Therefore, the exact value of the blockage factor predicted at the Sanal flow choking condition, corresponding to any fluid with the known HCR, could be taken as an infallible data worldwide for the certification, confirmation and standardization of various computational fluid dynamics (CFD) flow solvers authentically for meeting the future needs of various high fidelity multiphase and multispecies in silico simulations. This was an unresolved worldwide scientific problem for several decades.[1,11–24]

Though the basic governing equations of viscous flows were recognized for more than a century, until the theoretical discovery of the Sanal flow choking phenomenon,[1,5] there was no closed-form analytical model available for predicting the 3D blockage factor of any internal flow system. It is well known that the available mathematical methods are incapable to solve analytically the entire governing equations for viscous flows with any laminar or turbulence model. The in silico solution of the developing nonlinear system of equations is a challenging numerical task in the CFD even with a desirable higher-order accuracy ensuring the strong and competent solution using a better-quality and super-fine grid systems. Such a robust and efficient solution is desirable or rather inevitable for solving

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wall-bounded compressible fluid flow problems, where the blockage factor considerably influences the system performance. It is generally anticipated that when the resolution improves through grid refinement exercises, the in silico solution will not alter much and will accost the asymptotic value (i.e., the true solution). Admittedly, the errors will still persist between the asymptotic value and the true physical solution to the equations.[11,15] Roache,[15] stated that the verification of the in silico results involves error estimation, whereas verification of CFD codes involves error evaluation, from the standard benchmark data. And the best benchmark data are the closed-form analytical solutions with adequately intricate solution structure; they need not be rational since verification is a purely mathematical exercise.[15] Therefore, the exact solution generated from a mathematical model satisfying all the conservation laws of nature, which is wonderfully insensitive to discretization errors and totally untied from any type of empiricism is a feasible choice for achieving the true physical solution, wherever possible, which the Sanal flow choking model offers.[1] All these deliberations established herein that, the theoretical discovery of the Sanal flow choking phenomena is a scientific breakthrough and a paradigm shift in the CFD code verification. Furthermore, it is a useful tool for solving many unresolved problems carried forward over the centuries in physical, chemical, and biological sciences. One such problem of urgency was to predict the exact 3D blockage factor of real-world internal fluid flow systems for the CFD code verification, validation, and calibration with credibility. At this juncture, the experimentalist cannot provide the reliable benchmark data on the 3D blockage factor due to the inherent inability of the data acquisition through any available nonintrusive measurement technique. Note that in vitro data generally contains a certain level of error related to the complexity of the test-setup. It is reported (2017) that,[25] the data of each test are influenced by various statistical convergence levels and/or marginally different in vitro test conditions. So evidently, an accurate in vitro measurement of the 3D blockage factor is a very complex mission. Therefore, essentially one must trust upon any closed-form analytical model discovered based on real-world flow physics and fluid chemistry; and herein the Sanal flow choking model[1,5] provides the luxury to the scientific community for solving several unresolved problems carried forward over the centuries in physical, chemical and biological sciences. Therefore, we are critically reviewing the various applications of the revolutionary Sanal flow choking models herein for giving more physical insight into the internal flow choking phenomena in base fluids and nanofluids at the creeping inflow conditions for pinpointing various unresolved multiphase and multispecies biofluid dynamics problems for the drugs discovery for humankind.

The prediction of the 3D blockage factor with the molecular precision at the condition prescribed by the Sanal flow choking model is a breakthrough in the central science for elucidating the real-world fluid flow problems with credibility.[1,5,6] The fact is that the 3D blockage factors estimated at the Sanal flow choking conditions for both adiabatic and diabatic fluid flows are ground-breaking theoretical findings because these models could predict the CPR, which is a direct measure of the lower critical hemorrhage index (LCHI) and the lower critical detonation index (LCDI) in physical, chemical and biological fluid flow systems.[1,5–10] Note that, at the Sanal flow choking condition, the nondimensional 3D blockage factor is a unique function of the HCR and the incoming flow Mach number. And the CPR is a unique function of the HCR. Therefore, the estimation of the HCR is a meaningful objective for predicting the 3D blockage factor or vice versa at the Sanal flow choking condition of all real-world fluid flows. It is a well-conceded fact that problems inherent in the realization of in silico simulation of real-world flows embrace the complexity in denoting exact initial and boundary conditions and the difficulty in featuring volatile fluid flow characteristics.[2]

Certainly, all fluids in nature are compressible with different degrees of compressibility percentage, ranging from a zero-plus (0+) value,[26,27] as the specific heat at the constant-pressure (C_p) is always higher than the specific heat at the constant-volume (C_v) of all real-world fluids. During the in silico simulation, most of the previous researchers assumed that the human blood is an incompressible fluid,[28–36] and its C_p and C_v are identical. Although the results generated from such in silico models with the incompressible assumption will give numerical solutions within the specified degree of accepted accuracy for the prognosis and treatment of certain diseases and disorders, such an assumption is patently not true for solving several asymptomatic biofluid dynamics problems in numerous subjects (human being/animals) due to the large swings in blood pressure (BP) leading to cavitation and significant flow compressibility. The fact is that the human blood specific volume (or density) does change with temperature and/or pressure. Therefore, researchers must invoke the energy equation in their in silico simulation without prejudice to the creeping flow condition for generating reliable numerical results during the base flow and nanofluid flow analyses for solving high fidelity multiphase and multispecies numerical problems. Note that the specific heat capacity depends on the number of degrees of freedom and each independent degree of freedom permits the particles to store thermal energy and as a result the biofluid/blood heat capacity ratio (BHCR = $\gamma = C_p/C_v$) will be always greater than one, which is corroborated with the in-house experiments conducted in the National Center for Combustion Research and Developments (NCCRD) at IISc.[7–9] Note that during the traditional blood test across the globe the BHCR is not estimating for the diagnosis, prognosis, prevention and treatment of various diseases including the Covid-19, as its significance is still unknown to medical science. Note that the BHCR is regulating the CPR for the Sanal flow choking[1,5–10] condition in the base fluid as well as nanofluid, which is a remarkable finding reported herein first time for the risk assessment of catastrophic failure of any internal nanofluid flow system at the creeping inflow condition without any iota of symptoms of plaque deposit (atherosclerosis) or stenosis. In light of the Covid-19 pandemic, the BHCR alterations due to virus effects need to be examined due to the increased risk of cardiovascular diseases (CVDs), which was reported worldwide in Covid-19 patients. The European Society of Cardiology (ESC) reported (2020) that patients with cardiovascular risk factors and established CVD represent a vulnerable population when suffering from the Covid-19. ESC further reveals that patients with cardiac injury in the context of Covid-19 have an increased risk of morbidity and mortality (www.escardio.org).

In this review, we are presenting the closed-form analytical models and the infallible benchmark data generated from the exact solutions of the 2D and the 3D models developed at the Sanal flow choking condition for both adiabatic and diabatic internal fluid flows for conducting in silico experiments for the diagnosis, prognosis, management, and preclusion of detonation and hemorrhage in real-world fluid flow systems.

2. Backgrounds

The practice of in silico methods in fluid flow simulations, viz., fuel flow transportation in the chemical industry, cavitation simulation in water pipeline industries, the internal reacting flows modeling in combustors, fluid-structure interaction (FSI) in the circulatory system, biological fluid flow simulation during seasonal changes (diabatic flow conditions) and the multiphase and multispecies flow simulation in the nanofluid flow in chemical and biological sciences are emerging.[1–10] It is well known that the FSI, coupled with thermo-viscoelastic properties of materials, plays a key role in the circulatory circuit of human being and animals for predicting numerous diseases and disorders, viz., aneurysm (an excessive localized swelling of the wall of an artery), arrhythmia, hemorrhagic stroke and myocardial infarction (MI).[1,5–10] Since the artery and the solid rocket motor (SRM) grains are viscoelastic materials, the modeling and FSI simulation of biological fluid flow through the viscoelastic tube and the reacting flow simulation through the SRMs port are challenging in silico research topics of historical importance in central science. At the subsonic inflow condition, a dual-thrust SRM (see **Figure 1**a having a port similar to an artery with bifurcation (see Figure 1b)) experienced an undesirable high pressure spike followed by a catastrophic failure of the SRM at the static test stand.[6] The sonic-fluid-throat effect leading to the shock wave generation and the detonation were the actual causes of the high-pressure spike followed by the catastrophic failures of a few high-performance SRMs at the test stand. An analogous to the aforesaid physical situation experienced in a chemical rocket with divergent port; in biological systems, at the creeping inflow conditions the vascular system experienced asymptomatic aneurysm, arrhythmia, hemorrhagic stroke, and MI. Therefore, the benefits of the Sanal flow choking phenomenon in the diagnostic investigation of the detonation/hemorrhage in the real-world fluid flow systems are critically reviewed herein.

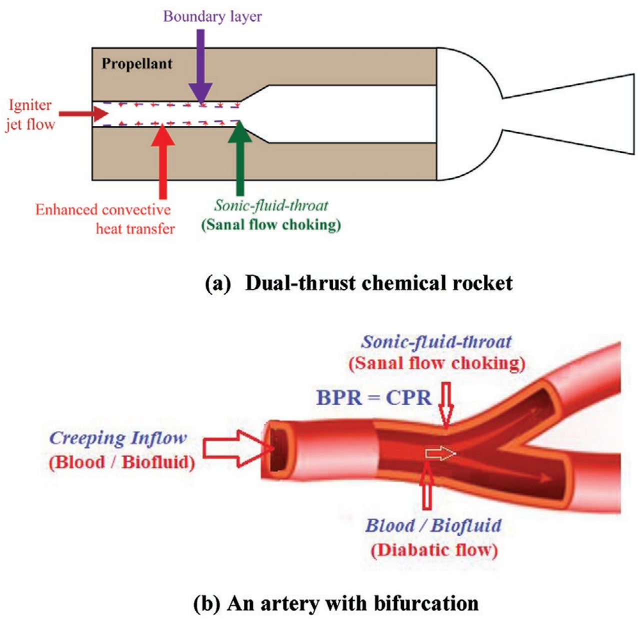


Figure 1. a,b) The phenomenon of Sanal flow choking in a chemical rocket and also in an artery with divergent/bifurcation region.

The prediction and the prohibition of detonation in chemical energy systems and that of the hemorrhage in the circulatory circuit of human being and animals, require the fundamental and multidisciplinary knowledge in applied science. The groundbreaking concept of the Sanal flow choking in the real-world fluid flow systems received significant attention in the physical, chemical, biological, and material sciences for the diagnostic investigation of the catastrophic failures of various internal flow systems without any preceding symptoms. The in silico simulation challenges in the chemical and aerospace industries resulted in getting a clear physical insight into how, when, and where the deflagration-to-detonation-transition (DDT) occurs.[1,6] In this review, the fundamental cause of the Sanal flow choking in a straight duct with the uniform cross-sectional area at the creeping inflow conditions is established. The nondimensional blockage factor is linked herein together with the average wall-friction coefficient, inflow Mach number, the HCR of the fluid and the total-to-static pressure ratio of the real-world internal fluid flow system. The authors observed that the detonation kernel is more susceptible to energy systems with sudden expansion/divergent port geometry producing the dominant reacting species with the lowest HCR. Subsequently, the authors detected that the hemorrhage is more prone to biological systems, typically in i) blood vessels with CD nozzle shaped passage (see **Figure 2**a–c), ii) artery having bifurcation and with or without stent (see Figure 2d–f), and iii) occlusion and/or collateral circulation through bifurcation regions of blood vessels (see Figure 2g) including vasa vasorum. Aforementioned physical situations are particularly true in all subjects (human being/animals) and it invites more danger when the circulatory system is encountered with any type of gas embolism (either the entry of a foreign gas or through blood evaporation). All the above background discussions lead to say that the accurate estimation of the blockage factor and/or the CPR for the Sanal flow choking is a meaningful objective for estimating the LCDI and the LCHI. Furthermore, the Sanal flow choking model will be useful for in silico model verification, validation, and calibration for solving real-world fluid flow problems with credibility.

The undesirable detonation in any dual-thrust combustor could be eliminated by maintaining the total-to-static pressure-ratio (P_o/P), at the fluid-throat and/or at the sudden expansion or divergent port location of the combustor, lesser than the CPR (i.e., P_o/P < LCDI). In the biological systems the systolic-to-diastolic blood pressure ratio (BPR) must be lower than the LCHI (i.e., BPR < LCHI) for reducing the risk of asymptomatic stroke. These conditions could be achieved in the energy systems by increasing the HCR of the evolving gases or by

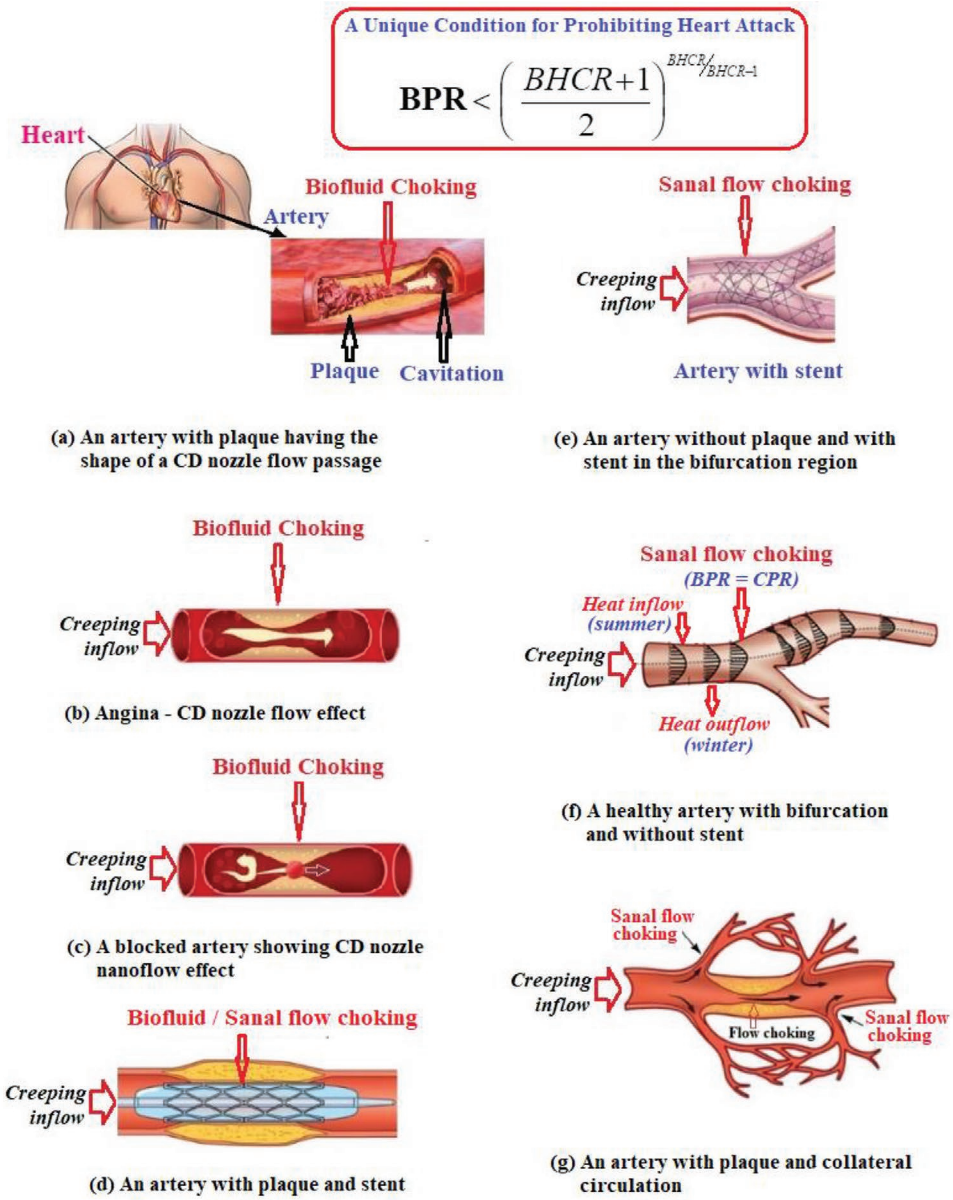


Figure 2. a–g) Demonstrating the biofluid choking and the Sanal flow choking situations in arteries and highlighting a unique condition for prohibiting the asymptomatic stroke and/or acute myocardial infarction irrespective of the artery blockage.

breaking the boundary-layer-blockage for negating the risk of Sanal-flow-choking or by reducing the BPR.

Certainly, the enhanced surface heating due to the boundary-layer heat transfer effects could accelerate flame spread in the port of any combustor with the large l/d ratio leading to an early DDT. The detonation kernel is more susceptible in dual-thrust combustors producing the dominant reacting species with low HCR. It is well known that the CPR (i.e., LCHI or LCDI) for flow choking is controlled exclusively by the HCR of the evolved gas. Therefore, a priori knowledge of the HCR of the evolved gas is essential for predicting the occurrence of Fanno flow choking, Rayleigh flow choking, and Sanal flow choking conditions in any wall-bounded fluid flow system.

Authors[1,5–10] reported that at the LCHI, the blood vessel with bifurcation and without any plaque and stent could experience the Sanal flow choking due to the blockage factor (Figure 2f) leading to asymptomatic hemorrhage/stroke as a consequence of the transient pressure overshoot as a result of the shock wave generation.[6] The research findings of the authors corroborated that,[1,6] at the Sanal flow choking condition, when the BPR reaches the LCHI anywhere in the circulatory circuit with sudden expansion or bifurcation region the chances of the physical occurrence of cavitation and shock waves are very high because of the off-designed CD nozzle-shaped-channel flow in blood vessels. Certainly, the Sanal flow choking is more severe near the heart valves, which create a CD nozzle flow effect leading to cavitation due to the geometrical shape or orientation of leaflets or cusps. In the case of fluctuating BPR the simultaneous choking and unchoking could lead to an arrhythmia. The similar physical situation in water pipe lines and flow valves are also experienced in the industry. The frequent occurrence of the Sanal flow choking leads to the defects in the pipeline and valves due to the undesirable cavitation and shock wave generation due to the formation of vapor pressure at the choked pressure ratio. The cavitation is an undesirable phenomenon in most of the internal flow systems, which could physically damage pipe lines and valves and create noise. In the industry, in most of the cases the downstream regions of the pipe lines are found damaged, which is corroborating our findings on the Sanal flow choking and cavitation leading to the shock wave generation and over pressurization as all fluids including water are compressible at a CPR.

The boundary-layer-blockage is more dangerous in any duct flow having sudden expansion or bifurcation region, which includes the circulatory circuit of all subjects because of the occurrence of the phenomenon of Sanal flow choking in an irregular CD nozzle type flow channel. Once the duct flow reaches the condition of the LCHI, abnormally high transient pressure overshoot could occur in the divergent region causing memory effects leading to an excessive localized swelling (aneurysm) at the downstream port of the duct leading to hemorrhage and/or myocardial infarction as the case may be.[6] Since SRM grains are made of viscoelastic materials there are chances of grain deformation due to the low relaxation modulus values and on the other hand there are chances of grain surface crack for cases with high relaxation modulus values due to the transient pressure overshoot due to the Sanal flow choking phenomenon at various test conditions. These physical situations altered the burning surface area of the SRMs, which would lead to the mission malfunction and/or failure. Until the discovery of the Sanal flow choking phenomenon the cause of such mission failures were unknown to the rocket industry.[5,6] It leads to say that the FSI simulation is essential for solving industrial problems with credibility using a well calibrated in silico model and its code of solution. Note that any CFD code verified and calibrated under the Sanal flow choking condition would be able to generate reliable in silico results for meeting the needs of the industry.

The Sanal flow choking phenomenon leading to a pressure spike observed in a dual-thrust chemical rocket (**Figure 3**a,b) opens a new avenue of research in the central science for accurately predicting the blockage factor for pinpointing the conditions of the occurrence of the Sanal flow choking phenomenon through reliable in silico studies worldwide with a priori knowledge of the HCR of the operating fluid and/or the gases evolved in internal flow systems.[1,5–10] The authors would like to emphasize herein that, the experiences gained through the various in vitro results established that the conventional incompressible assumption of water and blood are patently inaccurate for the high fidelity simulation because the HCR is found always higher than one as the specific heat at constant pressure is higher than the specific heat at constant volume ($C_p > C_v$) for these fluids at standard conditions.[7–9] The authors corroborated herein that both water and blood are compressible fluids. Therefore, the traditional assumption of water as an incompressible fluid will not survive henceforth

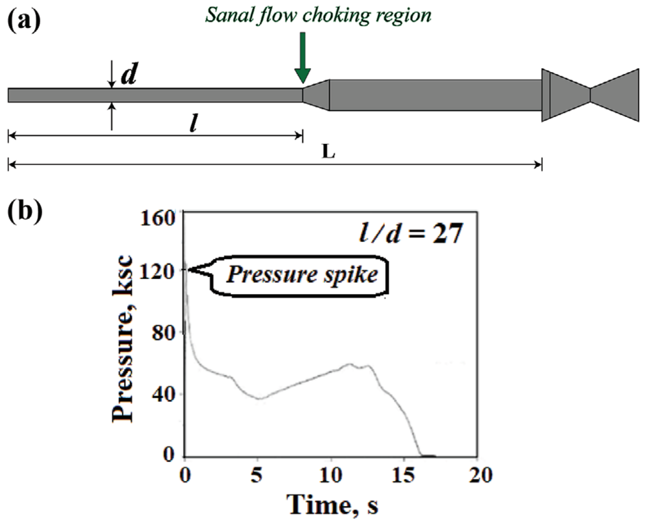


Figure 3. a) A typical dual-thrust rocket motor experienced the Sanal flow choking. b) The static test result of a dual-thrust rocket shows an unusual pressure spike due to the Sanal flow choking.

because the specific heat capacity is determined by the thermal energy of the particles in the substance, which is controlled by its number of degrees of freedom. All the real-world fluid flows experience the compressible fluid flow effect, which could lead to the Sanal flow choking condition at a CPR, which is uniquely determined by the HCR.

It is important to mention here that there was a general belief in the scientific community over the centuries that the creeping flow and/or the subsonic flow cannot be accelerated to the supersonic flow in a duct, with uniform port ending with a sudden expansion/divergence region (Figure 1b), without passing through a geometric throat.[1,3] The authors could disprove this general belief globally through the closed-form analytical models for both adiabatic and diabatic fluid flow conditions.[1,5,6] Accordingly, the popular research question, "how does the creeping flow and/or the subsonic flow get accelerated in a uniform cross sectional area duct leading to an internal flow choking due to the blockage factor?" was addressed cogently and conclusively herein with the closed-form analytical model capable to predict the Sanal flow choking for diabatic flows, which satisfies all the conservation laws of nature, for the CFD code verification and the diagnostic investigation of the detonation/hemorrhage in the real-world fluid flow systems with molecular precision.

2.1. The Sanal Flow Choking in Chemical Rockets

An accurate estimation of the 3D blockage factor is imperative for the design and development of high-velocity transient (HVT) dual-thrust solid (Figure 3a) and hybrid rockets (**Figure 4**), with the highest possible propellant loading density within the given envelope. It aims for the foolproof design optimization of the dual-thrust motors (DTMs) for the single stage to orbit (SSTO) vehicles without inviting any undesirable DDT in the combustor throughout the flight. During the development phase,[37–40] dual-thrust rockets with high propellant

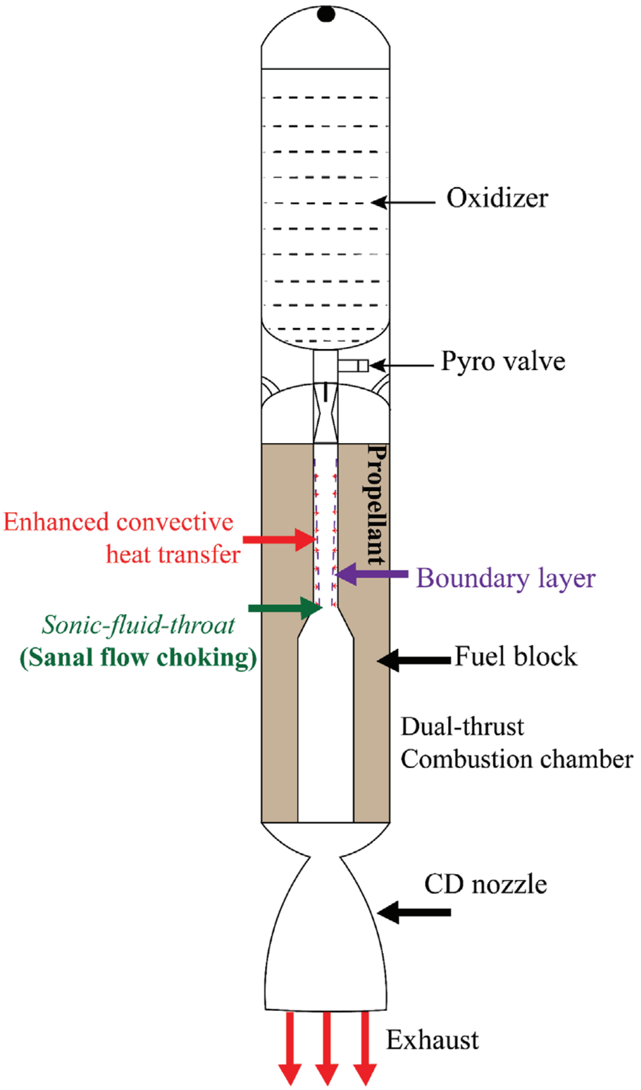


Figure 4. An idealized geometry of a dual-thrust hybrid rocket.

loading density (l/d > 27) experienced catastrophic failures at the subsonic igniter jet flow conditions during the ignition transient period of operation presumably due to an unexpected detonation due to the Sanal flow choking phenomenon.[1,5]

Kumar et al.[37–40] reported conclusively that at the subsonic inflow conditions, or at the creeping inflow conditions, after attaining the CPR in the flow system, there are the likelihood of the existence of the fluid-throat which induced the Sanal flow choking followed by shock waves leading to an undesirable sharp pressure overshoot in dual-thrust SRMs with high propellant loading density (Figure 3a,b) within the given envelope ($L/\mathrm{d} > 44$, $l/d \geq 27$). And the authors further highlighted that there is a limiting value of the l/d ratio in any dual-thrust chemical rocket, which determines the safe transition location for prohibiting the undesirable Sanal flow choking phenomenon. Using the Sanal flow choking model the chemical rocket designers could design the rocket motor with the maximum propellant loading density by fixing the l/d ratio within the safe limit for prohibiting the internal flow choking corresponding to the allied igniter jet Mach number and the HCR of the evolved gas in the upstream region of the port. The average wall-friction coefficient predicted[1] using the Sanal flow choking condition will come into to the picture during the in silico model verification. It is a useful input for the rocket designer to decide the propellant surface roughness for meeting the desirable ballistics. In a nutshell, the Sanal flow choking phenomenon is a remarkable finding for the integrated design of HVT chemical rockets and its allied igniters for improving the propellant loading capability for designing HVT hybrid rockets for SSTO vehicles with confidence. Note that the real physical situation of the sonic-fluid-throat effect creating the CD nozzle flow effect could occur in dual-thrust hybrid rockets too (Figure 4). Note that during the in silico simulation, the blockage factor value can be affected by the deviations in the adiabatic index or the HCR of the evolving gas and also due to the empiricism implicated in the conventional formulation of law of viscosity. Therefore, the accurate estimation of the blockage factor is predestined for a credible design optimization of any high performance dual-thrust chemical rocket. Literature review reveals that there were no evidence of internal flow choking during the test firing of dual-thrust SRMs (L/d = 13.39) at the US Naval Air Warfare Center (NAWC).[41] The motor geometric specifications of NAWC motors reveal that, the nonoccurrence of the internal flow choking in such motors were due to its low length-to-diameter ratio (L/d < 20).[42] Note that in light of the theoretical discovery of the Sanal flow choking in diabatic flows, the chemical rocket designer can further improve the propellant loading density of dual-thrust solid/hybrid rockets and/or NAWC tactical motors for improving its ballistic performance lucratively within the given envelope. The design optimization of such rocket motors could be accomplished with a priori knowledge of the CPR for the Sanal flow choking, which is uniquely controlled by the HCR of the evolved composite gases in the combustion chamber. In summary, designing a chemical rocket using the Sanal flow choking condition will be helpful for meeting the mission demanding thrust-time curves without the manifestation of any undesirable pressure overshoot and pressure-rise rate ($\mathrm{d}P/\mathrm{d}t$) for the future SSTO advanced aerospace vehicles.

Wang and Joseph[17] stated that in reality, the blockage factor is never zero and in most of the in silico simulation results the blockage factor is found to be pretty high, which invites substantial errors in predicting the internal flow features of real-world fluid flows. Therefore, a reliable estimation of the 3D blockage factor is inevitable for an accurate ballistic prediction of HVT dual-thrust solid or hybrid rockets. Note that the design of dual-thrust hybrid rocket motors entails a proper understanding of the physical phenomena that control the boundary layer combustion and the core reacting flow dynamic processes.[43–45] Though numerous analytical, in vitro, and in silico studies have been carried out comprehensively over the decades for exploring the boundary layer displacement thickness and the flow features of HVT chemical rockets, there were no unique model available until the discovery of the Sanal flow choking phenomenon (2018) for estimating the 3D blockage factors of such chemical rockets.[46] Henceforth, after invoking the Sanal flow choking condition, all the dual-thrust chemical rockets can be designed with the maximum propellant-loading-density with the highest payload capability within the given envelope without inviting any catastrophic failures, which often experienced by the space agency.[37–40]

2.2. The Sanal Flow Choking in Circulatory Systems

The modeling and simulation of physics of nanofluid is an active research topic of topical interest at the interface of the interdisciplinary approach for solving many unresolved real-world fluid flow problems carried forward over the decades for meeting the urgent needs of humankind.[47–50] One such problem of urgency is the biofluid/blood flow simulation of the circulatory circuit for the diagnosis, prognosis, prevention, and treatment of various asymptomatic vascular diseases,[34,51,52] which could enable delicate interventions in a manner that would be challenging or rather impossible in a traditional in vitro methods. Although in silico modeling of the base fluids and nanofluids have advanced significantly over the last few decades there are many unresolved problems in the real-world flows for a credible decision making through the high-fidelity numerical simulations. This is particularly true for the prediction and prevention of asymptomatic vascular diseases through cogent in silico experiments in nanofluids and biofluids with a far-reaching intention to explore the fundamental cause(s) of acute heart failure and asymptomatic stroke in all subjects (human being/animals).

Packer[53] reported (2018) categorically that the acute heart failure is an event rather than a disease and placed a cogent plea for a radical change in thinking and in therapeutic drug development through multidisciplinary research.[54] Kumar et al.[5–10] reported that such an event causing the acute heart failure is due to the biofluid choking (due to the plaque induced CD nozzle flow effect) and/or the Sanal flow choking (due to the boundary layer blockage induced CD nozzle flow effect) (Figure 2a–c). The vital fact is that the Sanal flow choking could occur in any artery with bifurcation and with or without any coronary artery stent (Figure 2d–g) due to the boundary-layer blockage factor due to viscous flow effect.

Discovery of Sanal flow choking[1,5,6] in the circulatory circuit calls for multidisciplinary and universal actions to propose novel therapies and to develop new drugs to reduce the risk of flow choking. Admittedly, the ischemic heart disease is the world's biggest killer.[55] Very commonly, the fatal MI happens without preceding symptoms of coronary artery obstruction (angina). The most common side effect of treatment with blood thinning medication is bleeding and very commonly asymptomatic aneurysm, hemorrhagic stroke and MI happen, which call for the application and the risk assessment of nanomaterials in the base fluids.[47–49] Of late, the undesirable pro and anticoagulant properties of nanoparticles in the base fluid epitomize major apprehensions in the arena of nanomedicine for promising interventions.[56,57] Over the centuries the risk for stroke and coronary heart disease have been correlated with BP level but there is no clear demarcation yet on the critical blood pressure level of any individual subject.[55–57] Note that asymptomatic vascular diseases have been reported for both hypertension and hypotension subjects. Therefore, the actual risk factors for acute MI are still unknown.[58–60] The fact is that the risk factor for acute MI is not the pressure but the CPR, which the authors are critically reviewed and reported herein. The accurate real-time data acquisition of the CPR is practically more difficult in multiphase and multispecies pulsatile nanofluid flow in the circulatory system and peristaltic flow of nanofluids in any internal flow system. Therefore, we need to rely upon closed-form analytical models.

The literature review reveals that due to the effect of the temperature gradient and thermophoresis, the nanofluid properties could vary radically within the boundary layer, which alters the nanofluid viscosity within the boundary layer and as a result pressure and the blockage factor will alter. Note that a decrease in viscosity of the creeping flow increases the Reynolds number, which could lead to laminar-turbulent transition.[61] Since the turbulent nanoflow boundary layer thickness is higher than the laminar nanoflow a decrease in viscosity leads to heat transfer enhancement in nanofluids, which increases the chances of an undesirable Sanal flow choking leading to shock wave generation and pressure overshoot due to the enhanced blockage factor. All these deliberations lead to establish that an accurate estimation of the blockage factor of nanofluid is a meaningful objective for conducting in silico experiments for various applications. This task is achieved through the theoretical discovery of the Sanal flow choking phenomenon for estimating the 3D blockage factor with molecular precision.

Of late, a multinational research team (Hayat et al.,[62,63] Khan et al., and[64] Muhammad et al.[65,66]) put considerable efforts for modeling the entropy generation with constant density in creeping nanofluid and ferrofluids flow with slip condition. Pandey and Kumar[67] carried out boundary layer flow and heat transfer analysis on Cu–water nanofluid flow over a stretching cylinder with slip. All these studies[62–67] would be useful for in silico simulation of creeping incompressible nanofluid flows. The authors can extend their modeling efforts by incorporating the compressibility condition, how so it is small, for reaching the physical situation of Sanal flow choking for solving the real-world nanofluid flow problems with credibility. Detailed discussion on in silico modeling of biofluid from creeping flow to Sanal flow choking condition in the circulatory circuit of a biological system is beyond the scope of this article. This review article is largely focused on the Sanal flow choking models and its application in solving adiabatic and diabatic compressible viscous fluid flow problems of topical interest.

It is abundantly clear from the literature that both the solid propellant grain and the blood vessels are having viscoelastic material properties and a priori knowledge of memory effects of such viscoelastic materials at multiaxial stress conditions are necessary for predicting the risk of vessel failures. Note that the relaxation modulus values of solid propellant grains and blood vessels could alter due to the transient pressure overshoot due to the shock wave generation as a result of the periodic Sanal flow choking as a consequence of the large pressure oscillations. The viscoelastic material properties of the vessels could also change due to the aging and seasonal changes. Therefore, the fluid-structural interactive code with multiphase and multispecies in silico simulation with due consideration of the memory effect (stroke history[6]) is a meaningful objective for forecasting the risk of the stroke/hemorrhage in the circulatory circuit of all subjects and the catastrophic failures of chemical energy systems. In a nutshell, the concept of the Sanal flow choking in the real-world fluid flow is a paradigm shift in the diagnosis of asymptomatic hemorrhage and ischemic heart disease.[1,5–10]

In addition to the analytical modeling efforts, authors have carried out in vitro studies for predicting the lower and the upper critical hemorrhage index (UCHI) of healthy subjects through the speciation analysis of blood for establishing the possibilities of the Sanal flow choking phenomenon in circulatory systems. The healthy males having age group 23–56 years with different blood groups are analyzed and compared with the blood test data of a healthy male Guinea pig of four weeks old.[7,9] During the hyphenated-techniques at the atmospheric pressure authors have detected predominantly N_2, O_2, CO_2, and Ar in blood samples of healthy subjects at various intensity at different temperatures, which are highlighting the physical situations of gas embolism in vessels corroborating the importance of solving biofluid flow problems with compressible flow assumption at various environmental and/or pathophysiological conditions. It is evident from the in vitro results (**Figure 5**a–c) that the chances of internal flow choking in the circulatory system of the human being is higher than the animal (Guinea pig) under the same thermal loading condition as the gasification temperature of healthy Guinea pig blood is found higher than the healthy human being.[7,9] The in vitro results provided a clear insight on in silico simulation at different thermal loading conditions. Accordingly, authors have established that all the researchers who are performing in silico simulation of biofluid/blood must invoke the flow compressibility at the creeping flow condition while solving multiphase and multispecies biofluid dynamics problems. Further discussion on this topic is beyond the scope of this review article.

It is apparent from Figure 5a–c that the potential occurrence of the biofluid choking in the circulatory circuit of the human being is higher than an animal (Guinea pig of 4 weeks old) under the same thermal loading condition as the specific heat ratio of the dominant gas evolved in a healthy animal blood is found consistently higher than that of healthy human beings. As a result, the lower critical hemorrhage index is found higher for the Guinea pig as dictated by the Equation (2a).[1,5] In the histogram the mass spectrum of N_2 is found higher in an animal blood whereas in human beings CO_2 is found higher. The heat capacity ratio of N_2 is 1.4 and that of CO_2 is 1.289. At this thermal loading condition, the artery of the Guinea pig gets choked only at a BPR of 1.8929 and the human artery gets an early choking at a BPR of 1.8257. Therefore, the authors concluded that the thermal tolerance level of the healthy Guinea pig is higher and the cardiovascular risk is lower than the human being under identical conditions.[1,5–10] These findings are corroborating with the recent articles published in the New England Journal of Medicine.[68,69] Of late, the authors reported that using aspirin to reduce the viscosity augments Reynolds number, which leads to high turbulence and enhanced boundary layer blockage (the peak during winter) creating an early undesirable cavitation, choking and shock waves in vessels.[10] The authors established that, flow turbulence enhances the loss of energy in the form of friction, which augments the boundary layer blockage in the blood vessels and generates heat and intensify the internal energy causing a decrease

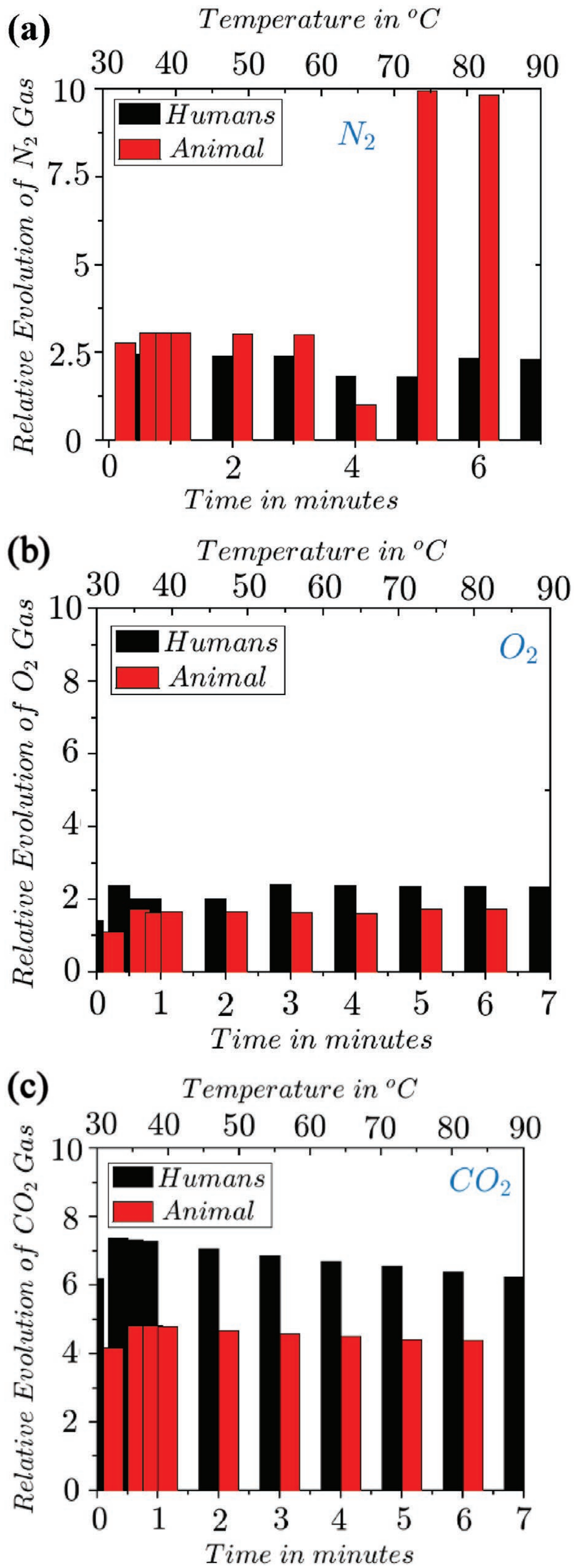


Figure 5. a–c) The mass spectrum of N_2, O_2, and CO_2 evolved as a function of both time and temperature during the speciation analysis of blood samples of healthy subjects.

in the HCR and is susceptible to an early Sanal flow choking. The sporadic Sanal flow choking, due to large swings in BPR, leading to transient pressure spikes developed over the years in the blood vessels make the vessel walls more stiff due to memory effects, which are prone to rupture in the subsequent Sanal flow choking. The authors concluded that the risk of biofluid or the Sanal flow choking leading to asymptomatic vascular diseases could be reduced by simultaneously decreasing the blood viscosity and the turbulence by increasing the HCR or decreasing the BPR.

All these findings lead to conclude that the lopsided blood-thinning medication could increase the risk of the Sanal flow choking causing asymptomatic stroke. Therefore, reliable in silico experiments are inevitable for the drug discovery for prohibiting the risk of Sanal flow choking for meeting the conflicting requirements in the circulatory circuit, viz., simultaneously reducing the turbulence level and viscosity. Note that discovering a nano medicine or a drug capable to increase the HCR of blood/biofluid within the pathophysiological constraints of each subject is a meaningful objective for prohibiting the biofluid choking and the Sanal flow choking in biological systems. Briefly, for increasing the healthy life span of all subjects, the BPR must always be lower than CPR dictated by the HCR of the blood/biofluid for prohibiting asymptomatic vascular diseases. Further discussion on this topic is beyond the scope of this review article.

3. Analytical Methodology

The Sanal flow choking occurs at the fluid-throat in a wall-bounded problem when the velocity at the blockage region (V_{BR}) attains the local sound velocity (a_{BR}), i.e.

$$a_{\mathrm{BR}} = V_{\mathrm{BR}} \tag{1}$$

According to the compressible fluid flow theory,[1,3] the total-to-static pressure ratio is an exclusive function of the HCR (γ) of any fluid at the choked flow condition, which gives the CPR value (Equation (2))

$$\mathrm{CPR} = \frac{P_{\mathrm{total}}}{P_{\mathrm{static}}} = \left(\frac{\gamma+1}{2}\right)^{\gamma/\gamma-1} \tag{2}$$

It is important to note here that, the existence of the condition for attaining the Sanal flow choking phenomenon in any wall-bounded air flow system (**Figure 6**) with the large l/d ratio (≥27) is very high.[1] Therefore, the prediction of the 3D blockage factor at the condition prescribed by the Sanal flow choking model in any industrial pipe line circuit with air bubbles is of notable technical interest for forecasting the pipeline defects locally due to cavitation and shock waves. In the case of dual-thrust SRMs and dual-thrust hybrid rockets, a priori knowledge of the blockage factor is inevitable at the given incoming jet flow Mach number, for the grain port geometry tailoring of the HVT dual-thrust SSTO vehicles. In light of the theoretical discovery of the Sanal flow choking phenomenon in the real-world fluid flows the following conditions (Equations (2a), (3), and (3a)) are set for predicting the LCDI and LCHI

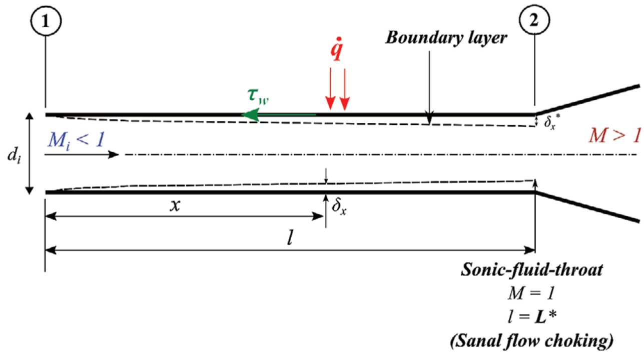


Figure 6. Demonstrating the Sanal flow choking phenomenon in a straight duct with divergent region leading to supersonic flow ($M > 1$) at the creeping inflow condition.

with the lowest value of the HCR (γ) of the evolved gases for avoiding the catastrophic system failures due to the sonic-fluid-throat induced shockwaves and detonation

$$\mathrm{LCDI} = \mathrm{LCHI} = \frac{P_{\mathrm{total}}}{P_{\mathrm{static}}} < \left(\frac{\gamma_{\substack{\text{evolved gases}\\ \text{with the lowest }\gamma}} + 1}{2}\right)^{\gamma_{\mathrm{lowest}}/\gamma_{\mathrm{lowest}}-1} \tag{2a}$$

$$V_{\text{fluid velocity}}\sqrt{\frac{\text{fluid density}}{\gamma\, P_{\mathrm{static}}}} < 1 \tag{3}$$

$$\left[\frac{(\text{Mass flow rate})_{\mathrm{local}}\,(\text{velocity})_{\mathrm{local}}}{\gamma_{\mathrm{lowest}}\; P_{\mathrm{static}}\,(\text{duct cross section area})_{\mathrm{local}}}\right]^{1/2} < 1 \tag{3a}$$

The lowest specific heat ratio of the evolved combustion gas could be found out through the speciation analysis.[9] Equations (2a), (3), and (3a) are the conditions set for prohibiting the Sanal flow choking phenomenon in any wall-bounded fluid flow system, which are derived from the compressible fluid flow theory.[3] Equation (3a), reveals that a decrease in the heat capacity ratio, a decrease in static pressure (diastolic blood pressure in the case of biological systems), and a decrease in the local cross sectional area of the duct or blood vessel (the effect of stenosis or block in the case of biological systems) occuring jointly or individually could increase the risk of Sanal flow choking, which are corroborating with the clinical and nonclinical findings available worldwide.[6–10] Additionally, an increase in the fluid flow rate and the local fluid velocity could increase the risk of Sanal flow choking. The noncatalogued clinical data are supporting these findings.

3.1. The Review of Closed-Form Analytical Models

An idealized physical model of a circular duct ($l/d_i \geq 27$) with divergent port is shown in Figure 6. Mathematical models for predicting the blockage factors for both 2D and 3D internal fluid flow through a circular duct at the condition prescribed by the Sanal flow choking models are presented herein as Equations (4)–(6)[1,5,6,70] in Sections 3.1.1, 3.1.2, and 3.1.3.

It is pertinent that, the inlet condition needs to be specified for achieving the real-world fluid flow condition prescribed by the Sanal flow choking in any wall-bounded geometry with any working fluid of known HCR. Note that for estimating the desirable inlet Mach number for attaining the Sanal flow choking in an adiabatic flow, the Fanno flow[3] choking condition is equated with the fluid-throat induced choking condition (see Equation (6) in Section 3.1.3). And for the diabatic flow systems for estimating the inlet Mach number, the condition set for the thermal choking[3] is equated with the blockage factor induced Sanal flow choking (see Equation (7) in Section 3.1.4).

3.1.1. Estimation of the 2D Blockage Factor

$$\frac{2\delta_x}{d_i}=1-\frac{M_i}{M_x}\left[\frac{1+\frac{\gamma-1}{2}M_x^2}{1+\frac{\gamma-1}{2}M_i^2}\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{4}$$

3.1.2. Estimation of the 3D Blockage Factor

$$\frac{2\delta_x}{d_i}=1-\left[\frac{M_i}{M_x}\right]^{1/2}\left[\frac{1+\frac{\gamma-1}{2}M_x^2}{1+\frac{\gamma-1}{2}M_i^2}\right]^{\frac{\gamma+1}{4(\gamma-1)}} \tag{5}$$

3.1.3. Estimation of the Inlet Mach Number for the Choked Adiabatic Flows

$$\frac{1}{M_i}\left[\frac{\gamma+1}{2+(\gamma-1)M_i^2}\right]^{1/2}=\left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \tag{6}$$

3.1.4. Estimation of the Inlet Mach Number for the Choked Diabatic Flows

$$M_i=\frac{1}{\gamma^{1/2}}\left[(\gamma+1)\left(\frac{2}{\gamma+1}\right)^{\gamma/\gamma-1}-1\right]^{1/2} \tag{7}$$

3.1.5. Analytical Prediction of the Average Friction Coefficient

$$\bar{f}=\frac{d_i}{4L^*}\left[\frac{1-M_i^2}{\gamma M_i^2}+\frac{\gamma+1}{2\gamma}\ln\left[\frac{(\gamma+1)M_i^2}{2+(\gamma-1)M_i^2}\right]\right] \tag{8}$$

where $\bar{f}$ is an average friction coefficient defined as

$$\bar{f}=\frac{1}{L^*}\int_0^{L^*} f\,dx \tag{8a}$$

3.1.6. Entropy Estimation at the Sanal Flow Choking for Diabatic Flows

$$\left(\frac{s_2-s_1}{C_p}\right)_{\text{Sanal Flow}}=\ln\left[\left(\frac{M_2}{M_1}\right)^{3\gamma-1/\gamma}\left(\frac{1+\gamma M_1^2}{1+\gamma M_2^2}\right)^{\gamma+1/\gamma}\left(\frac{1+\frac{\gamma-1}{2}M_1^2}{1+\frac{\gamma-1}{2}M_2^2}\right)^{\gamma+1/2\gamma}\right] \tag{9}$$

The models predicting the nondimensional blockage factor for the unchoked flow conditions of 2D and 3D wall-bounded problems are presented in Equations (4) and (5), respectively. At the choked flow condition (when Mach number, $M_x = 1$) the nondimensional blockage factor is an exclusive function of the inlet Mach number (M_i) and the HCR (γ). The 3D blockage factor presented herein as Equation (5) is a prominent mathematical model, which could forecast the possibilities of Sanal flow choking in any wall-bounded 3D cylindrical flow system from the known values of HCR. Note that the altered variations of HCR could alter the blockage factor and the LCDI/LCHI, as the case may be.

Figure 7 shows the solution curves of Equation (5) for predicting 3D blockage factor. Figure 7 is a very useful chart for the in silico experiments for both choked and unchoked flow conditions. While performing in silico experiments, for arriving the condition for Fanno flow choking at the sonic-fluid-throat, the average friction coefficient ($\bar{f}$) must be chosen in accordance with the l/d ratio of the duct or vice versa as decreed by Equation (8).[1,3] Through this prudent approach the effect of the shear stress could be included in silico model without any empiricism with respect to the friction factor, which warrants to obtain an exclusive value of the 3D blockage factor for a reliable standardization of in silico models and its code of solutions for solving the real-world fluid flows. The Equation (8) is a cogent mathematical model for predicting the average friction coefficient, which the CFD community was waiting for decades for in silico experiments and also for the model verification with credibility. The average friction coefficient chart of a choked internal flow system, named as Vicky Graph is presented in **Figure 8**a,b.

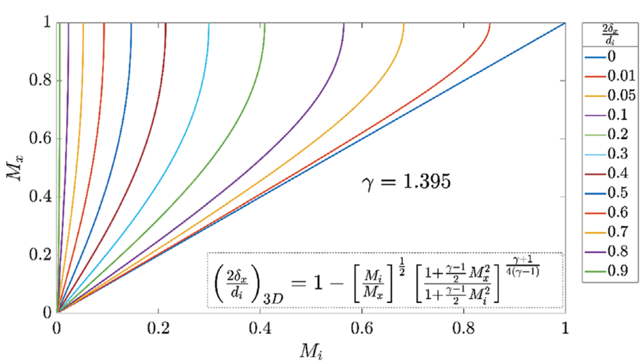


Figure 7. The 3D blockage factor (the solution curve of Equation (5)).

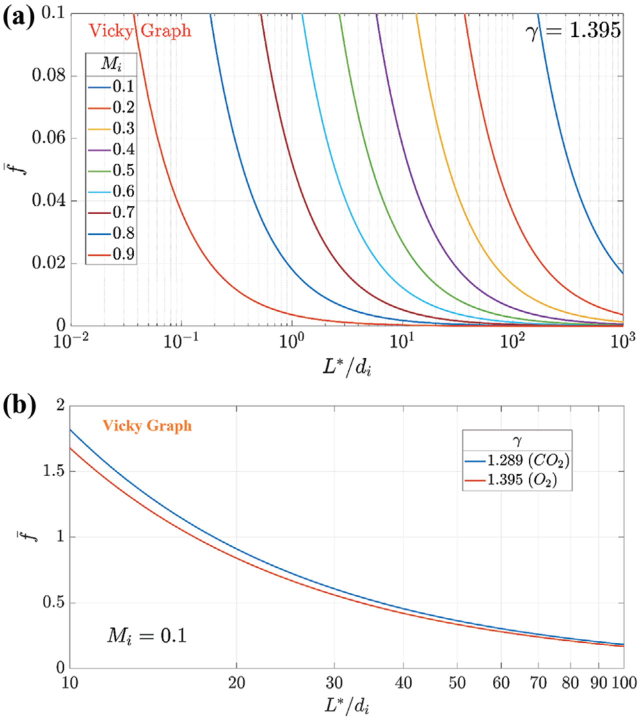


Figure 8. a) The Vicky Graph shows the analytical predictions of the average friction coefficient of a choked internal flow system at different subsonic inflow conditions. b) Comparison of the average friction coefficient of a choked internal flow system at a low subsonic inflow condition with two different working fluids.

Through this innovative analytical approach, the authors could capture the real-world fluid flow effects at the sonic-fluid-throat of wall-bounded problems at the given prudent inflow condition.[1] The analytical models reviewed and presented herein are having universal application and could be treated as universal benchmark models for in vitro, in silico and in vivo studies. More specifically, the experimentalists could calibrate their instruments and the viscous flow code inventors and users could validate, verify and calibrate the models and the code of solution at the conditions prescribed by the Sanal flow choking models with credibility for generating high fidelity data base for adiabatic and diabatic fluid flow cases (see **Table 1**, the Vigneshwaran's table of benchmark data).

Figure 9a, generated using Equation (9), is demonstrating the Sanal flow choking condition satisfying the real-world fluid flow effect. Note that Equation (9) is giving the entropy relation for the Sanal flow choking model ($M_i = M_1$) for real-world flows,[2,3] as the change in entropy is zero at $M_1 = M_2 = 1$. It corroborates that all conservation laws are satisfied in the sonic-fluid-throat location at the Sanal flow choking condition. As seen in Figure 9b, in all the three flow choking models, viz., Fanno flow,[3] Rayleigh flow,[3] and Sanal flow,[5] the change in entropy is zero at the sonic-fluid-throat point. Therefore, this methodology is declared as a foolproof analytical technique for exactly predicting the 3D blockage factor of the real-world fluid flows.

The infallible universal benchmark data obtained from the closed-form analytical models satisfying the conditions prescribed by the Sanal flow choking models are given in the Vigneshwaran's table (see Table 1). Table 1 gives the estimated inlet Mach numbers and the corresponding nondimensional blockage factor at Sanal flow choking condition of various gases with known HCR for both 2D and 3D problems along with the CPR = P_0/P^*, as an indicator of the LCDI or LCHI as the case may be for a credible in silico model verification, validation and calibration.

It is important to note that at the same inlet conditions the 3D blockage factor at the Sanal flow choking is found to be 47.32% lower than 2D adiabatic case and 45.12% lower than the 2D diabatic case with air as the operating fluid. This is an amazing and historical theoretical discovery to the global scientific communities for massive industrial applications worldwide.

Figure 10a,b shows the analytical mapping of the CPR and the blockage factor in a nondimensional scale for the real-world compressible fluid with the HCR ranging from 1 to 3 with a minimum inlet Mach number of 0.4 for adiabatic and diabatic fluid flow cases for both 2D and 3D cases. Note that Figure 10 is a useful tool for the CFD code verification, validation, and calibration with confidence.[71,72] As seen in Table 1 and Figure 10 the blockage factor is relatively higher for diabatic flows than adiabatic flows, which is a useful input to the CFD community for in silico code verification through the conditions prescribed by the Sanal flow choking models corresponding to any type of real-world flow. In the case of simulating the real-world fluid flow from the creeping in flow condition to the Sanal flow choking condition, the in silico model must be verified, validated and calibrated based on the average friction factor presented in Figure 8. The significance of the methodology reviewed herein is that, the models are fabulously unaffected to the errors due to discretization and fully freed from empiricism for a credible decision making on various high fidelity in silico data generated from creeping flow to supersonic flow.

3.2. The Estimation of the Blockage Factor from the In Silico Results

Historically, in the theory of boundary layers all the researchers worldwide invoked widely the blockage factor in the integral methods for 2D cases as a tool for various applications, as its description is explicit[37] and it is presented herein as Equation (10). Admittedly, until the dissemination of Sanal flow choking models for 3D cases for adiabatic and diabatic cases,[1,5,6] there were no authentic answers on the exact values of the 3D blockage factor of wall-bounded problems at any physical situation. Therefore, we have reviewed these models and its direct applications herein

$$\delta_x = \int_0^{d_i/2} \left(1 - \frac{\rho_x(y)\,u_x(y)}{\rho_\infty U_\infty}\right) dy \qquad (10)$$

The following analytical expressions (Equations (11)–(14)) are recommended to estimate the 3D blockage factor from the in silico results, which are formulated based on the law of conservation of mass

Table 1. Vigneshwaran's table of benchmark data.

Analytical prediction of the nondimensional blockage factor for 2D and 3D cases at the Sanal flow choking conditions for adiabatic and diabatic flows									
Sl. No.	Type of gas	γ	Adiabatic flow condition			Diabatic flow condition			$\frac{P_0}{P^*}$ (CPR)
			M_i	2D case $\left(\frac{2\delta_x^*}{d_i}\right)$	3D case $\left(\frac{2\delta_x^*}{d_i}\right)$	M_i	2D case $\left(\frac{2\delta_x^*}{d_i}\right)$	3D case $\left(\frac{2\delta_x^*}{d_i}\right)$	
1	Air	1.400	0.5613	0.1925	0.1014	0.4374	0.3247	0.1782	1.8929
2	Argon	1.667	0.5372	0.2052	0.1085	0.4236	0.3296	0.1812	2.0530
3	Butane	1.091	0.5950	0.1743	0.0913	0.4557	0.3181	0.1742	1.7048
4	Carbon dioxide	1.289	0.5726	0.1865	0.0981	0.4437	0.3224	0.1768	1.8257
5	Carbon monoxide	1.400	0.5613	0.1925	0.1014	0.4374	0.3247	0.1782	1.8929
6	Ethane	1.186	0.5838	0.1804	0.0947	0.4498	0.3202	0.1755	1.7630
7	Ethylene	1.237	0.5781	0.1835	0.0964	0.4467	0.3213	0.1762	1.7941
8	Helium	1.667	0.5372	0.2052	0.1085	0.4236	0.3296	0.1812	2.0530
9	Hydrogen	1.405	0.5608	0.1928	0.1016	0.4372	0.3248	0.1783	1.8959
10	Methane	1.299	0.5715	0.1871	0.0984	0.4431	0.3226	0.1770	1.8318
11	Neon	1.667	0.5372	0.2052	0.1085	0.4236	0.3296	0.1812	2.0530
12	Nitrogen	1.400	0.5613	0.1925	0.1014	0.4374	0.3247	0.1782	1.8929
13	Octane	1.044	0.6008	0.1711	0.0896	0.4587	0.3169	0.1735	1.6759
14	Oxygen	1.395	0.5618	0.1923	0.1013	0.4377	0.3246	0.1782	1.8899
15	Propane	1.126	0.5908	0.1766	0.0926	0.4535	0.3189	0.1747	1.7263
16	Steam	1.327	0.5686	0.1886	0.0992	0.4415	0.3232	0.1773	1.8488

$$\overline{\rho_x u_x} A_x = \int_0^A \rho_x u_x \,\mathrm{d}A = \sum_{i=1}^{n} (\rho u)_{x,i} A_{x,i} \tag{11}$$

For a cylindrical case Equation (11) can be rewritten as Equation (12)

$$\overline{\rho_x u_x}\left(\frac{d_i}{2} - \delta_x\right)^2 = 2\int_0^{d_i/2} \rho_x u_x r \,\mathrm{d}r \tag{12}$$

For a 3D cylindrical case Equation (12) is solved for getting the blockage factor, which is presented herein as Equation (13).

$$\delta_x = \frac{d_i}{2} - \left[2\frac{\int_0^{d_i/2} r\rho_x(r)u_x(r)\,\mathrm{d}r}{\overline{\rho_x u_x}}\right]^{1/2} \tag{13}$$

The 3D boundary layer blockage factor for a cylindrical case at the Sanal flow choking condition may also be estimated directly from the in silico results of Equation (14). The numerical methodology[73] involves integrating across the characteristic function of the entire cross-sectional area of a circular duct. Accordingly, the Equation (14) is derived from the concept of the missing flow rate in a circular duct for predicting the 3D blockage factor for the in silico code verifications.[3,73]

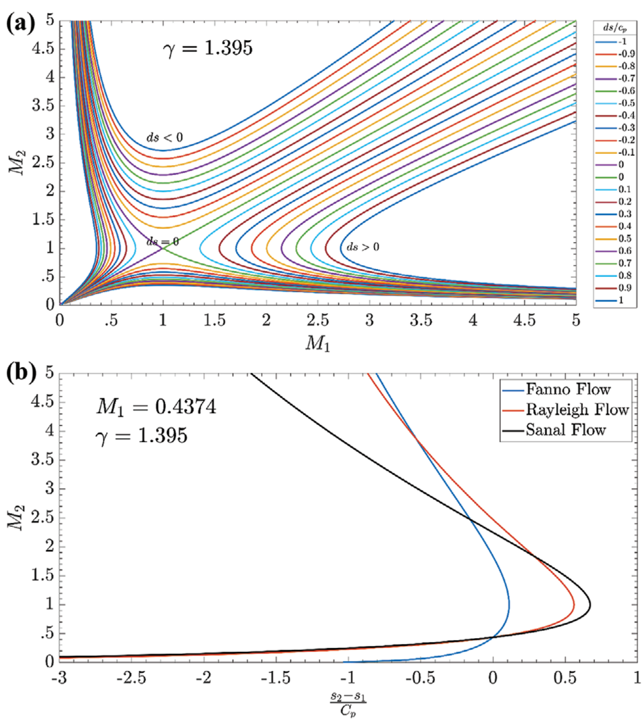
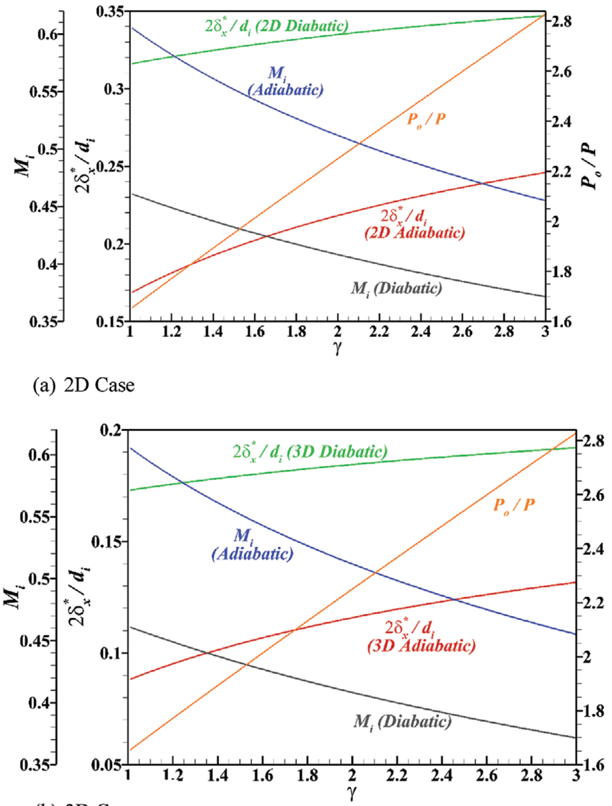


Figure 9. a) The demonstration of the Sanal flow choking condition satisfying the real-world fluid flow effect (solution curves of Equation (9)). b) The comparison of the entropy variations of three different flow choking models.



(a) 2D Case

(b) 3D Case

Figure 10. a,b) Benchmark data of the nondimensional blockage factor and the CPR at different HCR, and inlet Mach numbers for both 2D and 3D cases for adiabatic and diabatic cases.

$$\delta_x^2 - d_i\delta_x + 2\int_0^{d_i/2}\left(1 - \frac{\rho u}{\rho_\infty u_\infty}\right) r\,\mathrm{d}r = 0 \tag{14}$$

The integral is computed numerically from the data interpolated using the linear interpolation through a line along the radial direction at the sonic-fluid-throat of the cylindrical duct[73] for comparison with the exact solutions given in Table 1 for the CFD code verifications.

4. Discussion

The benchmark data generated from the Sanal flow choking models for adiabatic and diabatic flows are reviewed herein for both 2D and 3D cases. The authors proved conclusively that the exact values of blockage factors predicted at the Sanal flow choking conditions for various gases are the universal benchmark data for the in silico model verifications. At the Sanal flow choking conditions, the model presented herein for diabatic flows plays a pivotal role in the real-world fluid flow simulation and ensure that any flow solver with FSI code after invoking the thermoviscoelastic properties of materials, the rheology of fluid calibrated at the conditions prescribed by the Sanal flow choking models could predict accurately the existence of an internal flow choking due to the seasonal effect, Venturi effect and cavitation leading to shock waves and pressure overshoot. These models will enable us for solving many unresolved industrial problems in physical, chemical, and biological sciences and guide us for finding solutions for prohibiting the undesirable physical conditions of attaining the LCDI and LCHI in various fluid flow systems and subsystems. Venturi effect and cavitation are active research topics for several decades but yet there are many unresolved problems in industries allied with Venturi effect, cavitation and shock waves.[1,6,74–76] Note that as temperature increases the phase transition could occur in addition to the cavitation effect at different pressure levels in the water, chemical, oil and natural gas industrial pipe lines and any circulatory circuit including vasa vasorum. These are critical areas the researchers need to revisit for finding cogent solutions to the industrial problems in light of the findings on the CPR, cavitation, and the Sanal flow choking.

In order to predict the possibilities of the Sanal flow choking phenomenon in the circulatory system, the authors examined all the physical situations with the creeping flow condition, viz., with and without plaque, with and without stent, seasonal changes, the effect of blood-thinning medication, memory effects, leading to asymptomatic vascular diseases. The authors concluded that at the CPR the creeping flow will accelerate to the supersonic flow due to the CD nozzle flow choking effect due to the Sanal flow choking phenomenon. Note that at the choked flow condition the CPR is an exclusive function of the HCR. Admittedly, as on today there are no benchmark methods available globally for determining the HCR of biofluid/blood for predicting the critical systolic-to-diastolic blood pressure ratio for knowing the condition of the Sanal flow choking in the circulatory circuit. Therefore, in light of the infallible analytical methodology reviewed herein, future studies must be focused for estimating the BHCR for predicting the lower and the upper critical hemorrhage index for the diagnosis and prognosis of various unresolved problems in the biological sciences including the cardiovascular risk due to the Covid-19. The LCHI could be found out using Equation (2a) after substituting the lowest HCR among the evolved gases. This review article throws light in that direction for estimating the lowest HCR of the evolved gases in the circulatory circuit and also for finding the minimum temperature for gasification of blood samples of each and every subject for meeting the urgent needs of the human kind because it indicates the thermal tolerance level. Furthermore, the mathematical model developed under the condition of Sanal flow choking for diabatic flow is an innovation for the design optimization of HVT dual-thrust SSTO vehicles.

4.1. The Scientific Advances

A novel theoretical model for the entropy relation presented herein at the condition prescribed by Sanal flow choking phenomenon explains physics and the chemistry of the real-world fluid flow at the sonic-fluid-throat of any wall-bounded fluid flow system. The Sanal flow choking phenomenon prescribed herein for diabatic flows is a real-world fluid flow effect as it merges with Rayleigh and Fanno flow choking phenomena at a unique location of the sonic-fluid-throat. Therefore, the diabatic flow choking condition prescribed by the Sanal flow choking model plays a central science role in the in silico studies of real-world fluid flows. The model makes authoritative that any single or multiphase and/or multispecies viscous flow solver validated, verified and standardized with the diabatic flow choking condition prescribed by the Sanal flow choking model could be capable to forecast a priori the LCDI, which is a pointer to predict the DDT in real-world fluid flows with molecular precision. The in silico results will be more accurate if we invoke memory effect (i.e., stress/stroke history) coupled with variations in thermoviscoelastic properties and rheology of fluid. The significance of the solution methodology is that, all the conservation laws of nature are satisfied by the condition prescribed by the phenomenon at the Sanal flow choking for diabatic flows, which is established and reported herein as a universal benchmark data authoritatively. The exact numerical values of the blockage factors for various gases are reported in this review article as infallible benchmark data for both adiabatic and diabatic flows at the conditions prescribed by the Sanal flow choking models. Additionally, the closed-form analytical model adept to predict the 3D blockage factor for the real-world fluid flow presented herein is useful for the in silico model verification. Thereby, we could reexamine the suitability of the available turbulence models and the viscosity laws for a reliable decision making while solving high-fidelity industrial problems with molecular precision. Through our remarkable findings, we established that the exact value of the 3D blockage factor obtained at the condition prescribed by the Sanal flow choking model, with air as the working fluid, is 47.32% lower than the 2D adiabatic fluid flows and 45.12% lower than the 2D diabatic fluid flow case of any wall-bounded fluid-flow systems.

4.2. The Scientific Outlook

The universal benchmark data, taken from the exact value of the blockage factor of various gases at the condition prescribed by the Sanal flow choking model, derived from the conservation laws of nature presented herein could accurately identify the sources of errors of various fluid flow solvers for a credible in silico simulations for solving problems with interdisciplinary significance. This is particularly true in light of the advent of CFD simulations for solving problems in physical, chemical, and biological sciences. The authors conjectured herein that the subsonic reacting or diabatic flow, bounded with the streamlines having the shape of a CD nozzle flow passage would create detonation, when flow velocity inside the constriction region of the streamlines tube is same as the local velocity of sound. At this physical situation the shock waves could generate at the downstream divergent region of the streamlines tube when the upstream fluid-throat region attains the critical pressure ratio for choking, which is dictated by the specific heat ratio of the local species. The physical insight of the Sanal flow choking phenomenon presented in this review throws light for finding solutions for numerous unresolved problems carried forward over the centuries. We have concluded that Sanal flow choking models are applicable to all real-world wall-bounded problems including the water circulation circuit and the circulatory circuit of an anisotropic fluid like blood as both fluids are declared as compressible fluids henceforth.

4.3. The Overall Significance

The benchmark data generated using the Sanal flow choking conditions could accurately identify the sources of inaccuracies crept in various in silico models and its code of solution for a credible decision making while solving industrial problems with molecular precision. The closed-form analytical models reviewed and reported herein are capable to predict the condition for the shock wave generation, pressure overshoots, and DDT in real-world fluid flow systems with credibility. The theoretical discovery of the Sanal flow choking phenomenon of diabatic fluid flows is a paradigm shift in the in silico simulation and associated flow characterization based on different turbulent models and viscosity laws.

Through an authoritative mathematical model presented herein for predicting the 3D blockage factor, for establishing the sonic-fluid-throat effect, we could disprove the traditional belief in the central science over centuries that the subsonic creeping flow could not be accelerated to supersonic flow condition without passing through a geometric throat with the divergent duct at the downstream. In other words, the exact solutions generated from the Sanal flow choking models corroborate that even if the upstream jet flow Mach number is at the low subsonic flow conditions ($M_i < 1$) there are risks of attaining DDT in internal flow systems with the uniform port cross-section due to the sonic-fluid-throat effect. This finding got notable importance in all fluid flows in industry, viz., water pipeline industry for predicting the condition for cavitation and shock waves; fuel transporting in the chemical industry for predicting DDT; aeronautical and rocket industry for designing high-performance dual-thrust combustors with the highest solid fuel loading density within the allowable chamber size without inviting catastrophic failures due to the sonic-fluid-throat induced overpressure as a consequence of shock wave generation and detonation; and health care industries for predicting the condition for biofluid choking for estimating the LCHI. In a nutshell the discovery of the Sanal flow choking phenomenon is a paradigm-shift in the diagnostic sciences of stroke and ischemic heart disease as in silico model developers and users would get the universal benchmark data for their model verification, validation, and calibration for solving the nontrivial problems with credibility.

5. Concluding Remarks

Physics of sonic-fluid-throat disclosed herein at the Sanal flow choking condition for the diabatic flow is not merely an engineering topic of challenge, instead this review article emerges to expose the solution of any real-world fluid flow problems (base fluid/nanofluid) of topical interest to the advanced science community. It is well known that the internal flow choking creates transient pressure overshoot in the viscoelastic duct with sudden expansion and/or divergent region where the supersonic flow persists. Frequent pressure spikes, due to the pressure oscillations creating choking and unchoking conditions, could lead to an enhanced memory effect of the viscoelastic wall of the duct. The subsequent pressure overshoots due to the shock waves could invite catastrophic failures of the internal flow system as a result of the development of the onsite high-relaxation modulus, which is a useful input to a credible in silico simulation of biological fluid flows.

The coherent mathematical models presented in this review article are useful for the internal fluid flow systems design, by identifying the controlling parameters of internal flow choking, vessel geometry, inflow Mach number and the HCR of the fluid. Additionally, the rocket designers could make credible decisions for increasing the loading density of the solid propellant within the given envelope without inviting catastrophic failures due to the shock waves and detonation. Most importantly, the CFD code developers and users could obtain the benchmark data for the validation, standardization, and verification of the in silico models and its code of solutions for the high fidelity simulation of real-world fluid flow problems with reliability.

The mathematical model for diabatic flows presented herein gives an insight in the accurate estimation of the HCR, which is a pointer toward finding solutions to many fluid dynamics problems in the multidisciplinary domain. Of late (2019) Mariappan et al.[77] reported that cultivating medicinal plants in the international space station (ISS) is a possible option for the drug discovery for increasing the HCR of blood for reducing the risk of stroke.[5–10] Generally, in the circulatory circuits, blood flow is laminar. While using the blood thinners and/or drugs with the anticoagulant properties the dynamic viscosity of blood decreases and as a result Reynolds number increases and the laminar flow could be disturbed to turbulent flow, which could augment the blockage factor in the blood vessels and generates heat and augment the internal energy causing a decrease in BHCR, which increases the risk of stroke and MI. The closed-form analytical methodology reviewed herein corroborated that a vaccination to increase the BHCR could reduce the risk of stroke and MI by prohibiting the biofluid choking/Sanal flow choking. Additionally, the Sanal flow choking model corroborated that the stents are no better than medications. Further discussion on the prediction and the prevention of the stroke and the MI are beyond the scope of this review article. Briefly, the discovery of Sanal flow choking, in diabatic flows causing memory effects[6,78,79]in thermoviscoelastic composite walls, is a scientific breakthrough for further research in base fluid flow and nanofluid flow[80] problems in physical, chemical, material and biological sciences.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

chemical rocket design, code verification, fluid flows, heart attacks

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